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Transmission efficiency improvement of the injector line of SFC by particle beam decorrelation*

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The operation of the HIRFL accelerator has shown that the beam transmission efficiency of the sector focusing cyclotron (SFC) injector line is rather poor. Beam simulations have been performed to investigate the possible causes for this low transmission. It is predicted that the property of transversal coupling of the ion beam from electron cyclotron resonance (ECR) ion source can be an important factor to degrade the beam quality by increasing the beam emittance, resulting in a serious particle loss. An improved operation scheme for the SECRAL associated line has been proposed, and the corresponding experiment was carried out. This paper presents the test results.

Keywords: Electron cyclotron resonance, Emittance, Transverse, Coupling

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I. INTRODUCTION

Heavy Ion Research Facility at Lanzhou (HIRFL) [1, 2] consists of four accelerators in series, a sector focusing cyclotron (SFC), a separator sector cyclotron (SSC), a cooling storage synchrotron (CSRm), and a cooling storage synchrotron for experiment (CSRe). The SFC is the injector of SSC and an injector of CSRm, too, for light ions (SFC+CSRm mode), while the SFC and SSC work together to inject the CSRm with heavy ions (SFC+SSC+CSRm mode). Three ion sources are now serving the HIRFL, i.e., LAPECR1 (Lanzhou All Permanent magnet Electron Cyclotron Resonance ion source No.1), LECR3 (Lanzhou Electron Cyclotron Resonance ion source No.3) and SECRAL (Superconducting Electron Cyclotron Resonance ion source with Advanced design in Lanzhou) [3]. SECRAL is a fully superconducting electron cyclotron resonance (ECR) ion source dedicated for highly charged heavy ion beam production.

Operation of the SECRAL ion source has demonstrated its outstanding performance of high beam intensity. However, routine operation of the accelerator shows that beam transmission efficiency of the injector line from SECRAL to the SFC is just around 50%. Various hypotheses to explain this low transmission were proposed, mostly focusing on the buncher efficiency and alignment problem, without much convincing evidence for the hypotheses so far, though.

Recently, researches on transversal coupling property of ion beam from the ECR ion source were carried out [4]. It is predicted that this property can be an important factor to give rise to the projection transverse emittance blowup since the beam coupling is intensified by the solenoid lenses in the SECRAL associated line. An improved operation scheme for the SECRAL associated line was proposed on basis of beam simulations, that is to adjust the solenoid lenses to achieve a transversally decoupled beam so that the projection transverse emittances reaches minimum value. The experiment to verify this proposal indicates that by using this operation scheme, the beam transmission efficiency of the injector line of SFC can be increased to 75%. However, for high-intensity ion beams, the existing optical elements are incapable of creating a decoupled beam because of focusing requirement of the beam. A modification proposal of the Q/A selector system of the SECRAL is proposed, and the reasonability and feasibility are proven by simulations.

II. THE INJECTOR LINE OF SFC

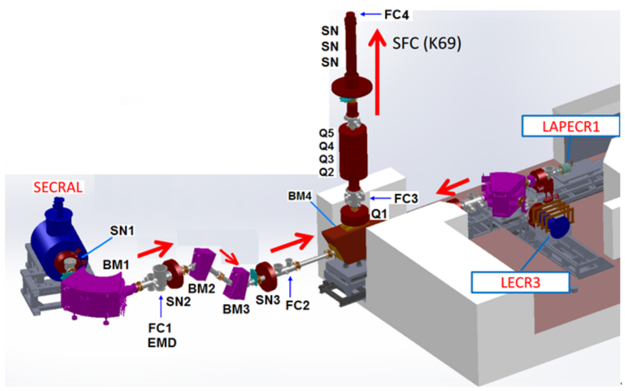

Fig. 1. (Color online) SFC injection line layout. SN,solenoid lens; BM, bending magnet; FC, faraday cup; EMD, emittance measuring device, and Q quadrupole.

A layout of the injector line for the SFC is shown in Fig. 1. It consists of three sections: the SECRAL associated line, the proton and medium mass ion beam line shared by LAPECR1 and LECR3, and the vertical line to reach the SFC, which

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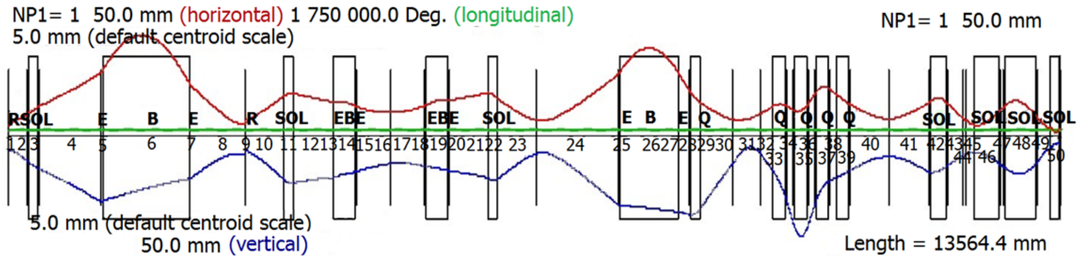

Fig. 2. (Color online) Simulated beam envelope with Trace3D.

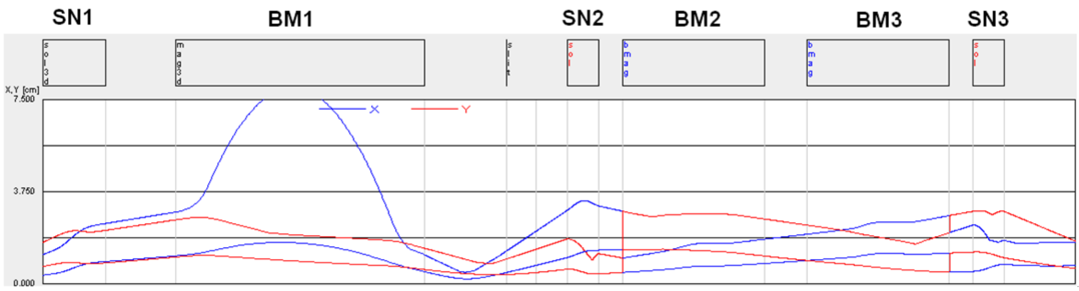

Fig. 3. (Color online) Simulated beam envelope from SECRAL exit to the FC2 with TRACK code.

is mainly composed by five magnetic quadrpoles (Q1–Q5), three solenoids before the SFC entrance, two longitudinal bunchers and one chopper (not shown). A dual-90-degree bending magnet BM4 is adopted as the transmission link to deliver the ion beams from ground level where ion sources are located to the vertical line.

The SECRAL associated line (from the ion source exit to BM4) includes three solenoid lenses (SN1, SN2 and SN3), three bending magnets (BM1, BM2 and BM3), and two testing chambers. After extraction from SECRAL, ion beams are initially focused by SN1. The wanted ion species are selected by BM1, a double focusing 110° analyzing magnet. After BM1 is a test chamber, where a faraday cup (FC1), a fluorescent target and Allison type emittance measuring device (EMD) are placed. Because BM4 is below the level of SECRAL, two identical 45° bending magnets (BM2 and BM3) are introduced to bend the beam vertically to reach BM4. Two identical solenoids, SN2 and SN3, are installed on each side of the dual-bending magnets to provide focusing forces to the beam. Another test chamber, equipped with only a faraday cup (FC2), is located behind SN3.

III. PARTICLE-IN-CELL (PIC) SIMULATION WITH A TRANSVERSE COUPLED BEAM FROM ECR ION SOURCE

The injection line was initially designed with Trace-3D program [5]. Figure 2 illustrates a simulated beam envelope for 25 kV $^{209}Xe^{29+}$ beam from SECRAL exit to the SFC entrance. Cross section of the beam from the ion source is assumed to be round and axisymmetric, having no correlation between horizontal and vertical projection phase space. However, for an ECR ion source, the ion density distribution across the extraction aperture is inhomogeneous, due to the magnetic confinement fields, hence the non-round cross section of beam along the transport path. When the ions are extracted and accelerated through the descending axial magnetic field at the extraction region, the horizontal and vertical phase space strongly coupled. Recently, transversal coupling property of the beam from ECR ion source was studied [4] and the beam coupling configuration was achieved in the 4-D phase space at the ion source exit for Xe^{29+} beam under 25 kV extraction voltage.

Due to periodic property of the coupling, the solenoid lens behind the ion source (SN1) can disentangle the coupling periodically by changing the focusing strength [4]. To achieve higher transmission efficiency, the ion beam should have the minimum projection emittance values both horizontally and vertically, that is, the ion beam should be transversally decoupled. This is because, determinant of the 4-D sigma matrix keeps constant for ion beams being both coupled and decoupled; but the product of horizontal and vertical projection emittance for beams being decoupled only can be minimized at the determinant of the 4-D sigma matrix. However, the solenoid lens SN1 is mainly used for initial focusing and size-control of the beam going into the analyzing magnet, and is responsible for tuning flexibility of the Q/A selector system for all kinds of ion species produced by the ion source [6]. Therefore, adjustable range of the solenoid lens current is limited. To find an optimal operation scheme in the SECRAL associated line, PIC (Particle-In-Cell) simulation was carried out by using TRACK code [7], in which the 25 kV $^{129}Xe^{29+}$ beam particle distribution in the 4-D phase space at the ion source exit (presented in Ref. [4]) was imported as the initial condition.

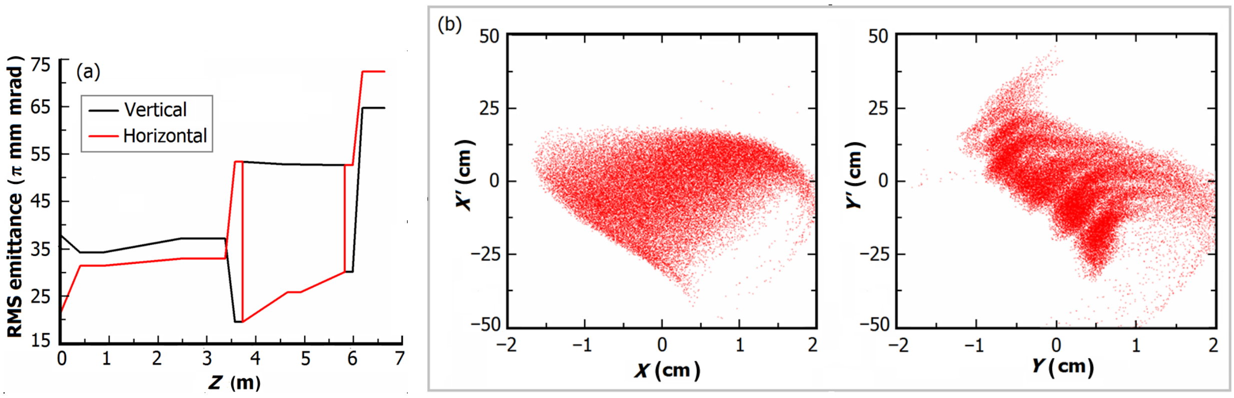

Fig. 4. (Color online) Beam emittance evolution in the SECRAL associated line (a) and simulated particle distributions in the phase space (xx' and yy') at the location of the FC2 (b).

Firstly, simulation was performed with the solenoid strengths corresponding with specifications in the initial design by Trace-3D. Figure 3 is the beam envelope from the ion source exit to FC2, with the fields of SN1, SN2 and SN3 being 2 455 Gs, 3 000 Gs and 3 000 Gs, respectively. It shows an asymmetrical beam, differing from the Trace-3D simulation (Fig. 2). Figure 4(a) is the beam emittance evolution along the line in both horizontal and vertical directions, showing that the beam emittance has an obvious blowup at FC2, with a serious distortion in the phase space, as shown in Fig. 4(b). Since space charge effect is not taken into account in this simulation by assuming the beam current of zero, the projection emittance growth is mainly due to the transversal coupling of the beam, plus slight effect of the aberrations in the magnets. That means in the existing operation scheme of the SECRAL associated line, the coupling of the beam from the ion source is intensified by the solenoid lenses and the horizontal and vertical projection emittances are therefore increased.

As mentioned before, to achieve the minimum projection transverse emittance, transversal coupling of the ion beam should be dissociated. It was described in Ref. [4] that when the solenoid lens SN1 is loaded with -180 A (corresponding field strength is of -2 455 Gs, the negative value of the solenoid lens current means the beam transmits in the opposite direction of the solenoid lens axial field in the beam pipe), the ion beam (25 kV $^{209}Xe^{29+}$) reaches a decoupled condition. However, the solenoid lenses SN2 and SN3 will also cause the transversal phase space coupling, because the ion beam still keeps asymmetric even though the SN1 has disentangled the initial coupling caused by the ion source. Since SN2 and SN3 have the same configurations, if these two lenses are loaded with the same current values but in opposite polarities, the combined transfer matrix of the two lenses will be like,

$$\boldsymbol{R} = \boldsymbol{R}_{\text{sol}+} * \boldsymbol{R}_{\text{sol}-} = \begin{bmatrix} \# & \# & 0 & 0 \\ \# & \# & 0 & 0 \\ \# & \# & 0 & 0 \\ 0 & 0 & \# & \# \\ 0 & 0 & \# & \# \end{bmatrix}, \qquad (1)$$

which will not give rise to a transverse correlation.

TABLE 1. Simulated horizontal and vertical projection emittances and their products at different field strengths of SN1, SN2 and SN3

SN1 (Gs)	SN2 (Gs)	SN3 (Gs)	ε_H (π mm mrad)	ε_V (π mm mrad)	$\varepsilon_H * \varepsilon_V$ (π mm mrad)^2
2 455	3 500	3 500	92.6	50.3	4 657.8
2 455	3 500	-3 500	62.9	66.5	4 182.9
2 455	-3 500	3 500	43.6	58.3	2 541.9
2 455	-3 500	-3 500	35.3	75.5	2 665.2
-2 455	3 500	3 500	29.4	30.5	896.7
-2 455	3 500	-3 500	10.7	44.3	474.0
-2 455	-3 500	3 500	9.7	48.6	471.4
-2 455	-3 500	-3 500	32.3	29.6	956.1

To verify this hypothesis, a series of simulations were done under different field strengths of SN1, SN2 and SN3. The projection emittances in both horizontal and vertical directions and their products are listed in Table 1. It can be seen that when the SN1, SN2 and SN3 fields are -2 455 Gs, 3 500 Gs and -3 500 Gs or -2 455 Gs, -3 500 Gs and 3 500 Gs, respectively, the projection transverse emittance is minimized, i.e. optimal condition of the ion beam. Figures 5 and 6 show the simulated beam envelope, projection transverse emittance evolution, and the phase space distributions under this condition. The transverse emittance in the horizontal (X) and vertical (Y) directions in Fig. 6(b) differ markedly from each other, with much smaller areas of the distribution, and far less serious distortions in the phase space, than those in Fig. 4(b).

IV. EXPERIMENTAL RESULTS

The above mentioned simulations provided a new operation scheme of the SECRAL associated line to improve the beam quality. That is, firstly, to adjust the solenoid lens SN1 to disentangle the coupling of the beam from ECR ion source and provide required focusing; and secondly, to make the solenoids SN2 and SN3 with different field directions but similar focusing strength. The vertical line takes the responsibility of matching the beam to the SFC. This scheme was

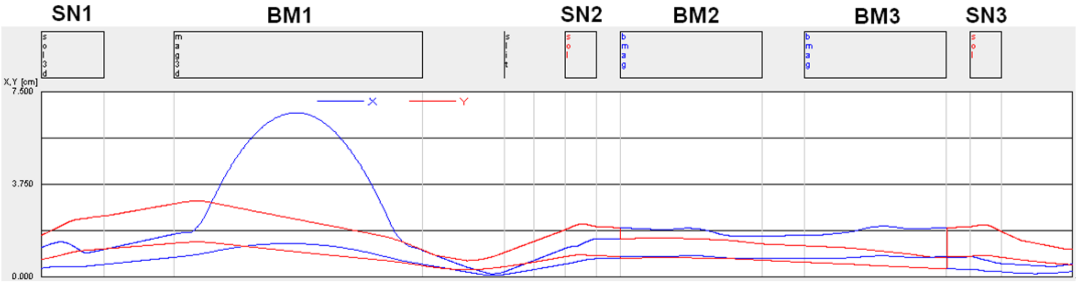

Fig. 5. (Color online) Simulated beam envelope with SN1, SN2 and SN3 fields of -2455 Gs, -3500 Gs and 3500 Gs, respectively.

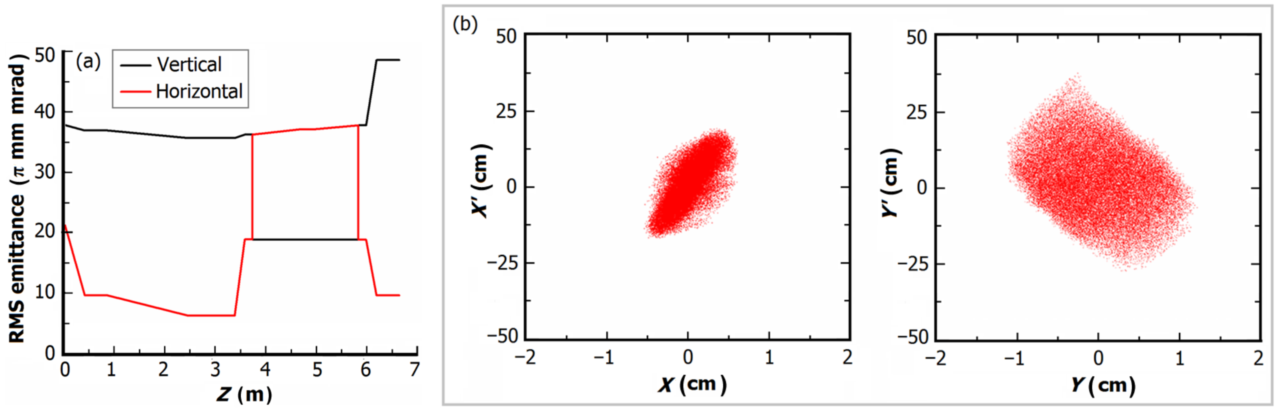

Fig. 6. (Color online) Beam emittance evolution (a) and simulated particle distributions in the phase space under conditions in Fig. 5.

tested in the recent accelerator operation for 18.9 kV ^{86}Kr^{17+} beam provided by SECRAL. The ^{86}Kr^{17+} beam currents measured at FC1, FC2, FC3 and FC4 (before injection, as shown in Fig. 1) and the extraction exit of SFC are 88 eμA, 81 eμA, 73 eμA, 66 eμA and 5.9 eμA, respectively. Therefore, transmission efficiency of the injector line to SFC can be estimated at 75%, which was 51% in previous operations; while the overall efficiency of SFC is 6.7% in this operation, which is almost doubled.

V. PARTICLE BEAM DECORRELATION FOR HIGH-INTENSITY ION BEAMS

As mentioned before, the primary role of SN1 is to provide a pre-focusing and size-control of the beam going into the analyzing magnet, which is especially effective for high-intensity ion beams, where the space charge effect becomes a main reason of beam divergence. Previous studies [6] indicated that increasing the initial focusing strength is beneficial to reduce the beam emittance growth by avoiding the large-radius aberration in the analyzing magnet [8]. As an example, Figure 7 shows a series of measured emittance under different solenoid currents after the analyzing magnet BM1 or at the position of the EMD for 110 eμA ^{40}Ar^{9+} beam with a total drain current of 1.7 emA under 23.6 kV of extraction voltage. A simulation was performed for the 25 kV ^{209}Xe^{29+} beam by taking the space charge effect into account. The projection emittances in both horizontal and vertical directions and their product under different solenoid field strengths are illustrated in Fig. 8. The trend of change in projection emittance agrees well with the phenomenon in the experiments. The minimum projection emittance exists when the solenoid field is the largest (-4 098 Gs).

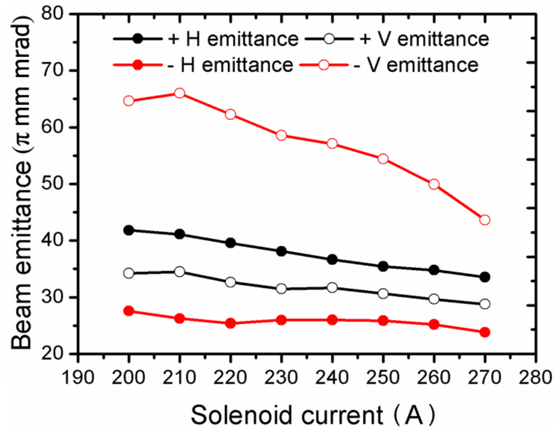

Fig. 7. (Color online) Measured beam emittances for ^{40}Ar^{9+} beam by changing the current of the solenoid lens SN1. ("+" means positive current being loaded on the solenoid, in which case the beam transmits in the direction of the solenoid lens axial field in the beam pipe; "—" means negative current being loaded on the solenoid; "H" means horizontal; "V" means vertical.)

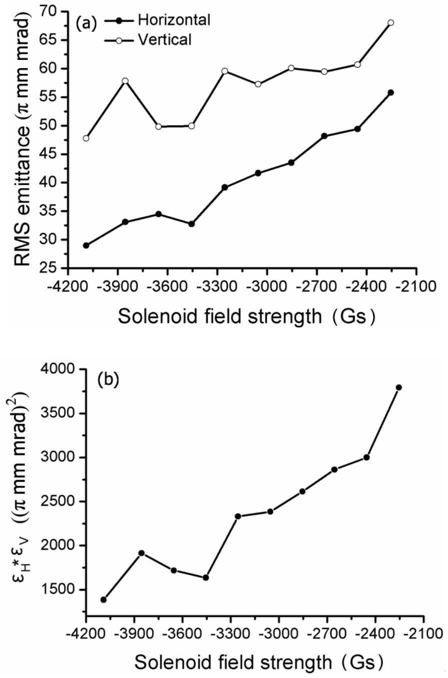

Fig. 8. Simulated beam horizontal and vertical projection emittances (a) and their product (b), for $25\,\mathrm{kV}\_{}^{209}\mathrm{Xe}^{29+}$ beam under different field strengths of the solenoid lens SN1.

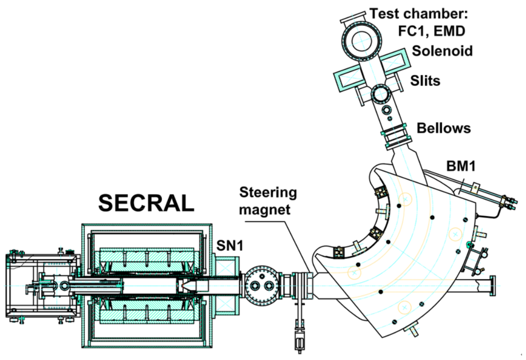

Fig. 9. (Color online) Layout of the improved Q/A selection system for SECRAL.

However, this is not the condition for the particle beam decorrelation (the corresponding field strength for the decorrelation is of -2 455 Gs as mentioned before), therefore, the particle beam is not of optimal quality. The question is how to meet the requirement of the beam focusing from SN1 and how to disentangle the coupling for high-intensity ion beams. It is clear that only one solenoid lens cannot accomplish these requirements. There must be at least one more optical element to be introduced, which can rotate the beam. A skew magnetic quadrupole or a solenoid can be a candidate. As a proposal, Figure 9 illustrates a modification scheme of the Q/A selection system, in which another solenoid is employed just between the slits and the test chamber for the coupling decorrelation compensation, where the wanted ion species can be selected. Figure 10 shows the simulated beam projection emittance and their product as a function of the compensation solenoid field strength at the SN1 field magnitude of -4 098 Gs. One can see from the figures that with help of the solenoid, the projection emittance is somewhat decreased and the product is minimized at the solenoid field of around 1 900 Gs, under which condition the ion beam can be considered as “decoupled”.

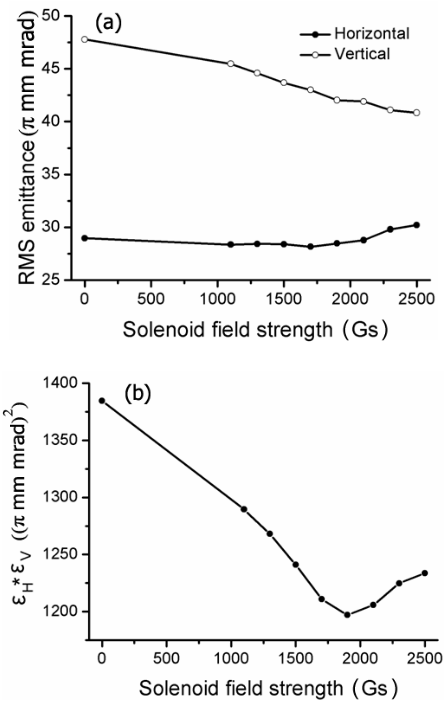

Fig. 10. Simulated beam emittances (a) and product of horizontal and vertical projection emittances (b), versus field strength of the solenoid.

VI. CONCLUSION

Beam simulations have been performed to investigate the injector line for the SFC on the basis of our recent research on the transversal coupling property of the beam from ECR ion source. It is predicted that one possible cause of the low transmission efficiency is that the coupling of the beam is intensified by the solenoid lenses in the SECRAL associated line, resulting in the projection transverse emittance blowup. An improved operation scheme for the SECRAL associated line has been proposed, that is firstly to adjust the solenoid lens SN1 to disentangle the coupling and then to make SN2 and SN3 have equal magnitude of field strength but opposing polarities. Experiment using this scheme was carried out, which shows the overall efficiency of SFC is almost doubled, and for the injector line increased by around 24%. In the last section of the paper, a modification proposal for the Q/A selector system of the SECRAL is proposed to deal with the high-intensity ion beams, which has been verified by a series of subsequent simulations and proven to be reasonable and feasible.

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